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ONRL Report C-2-85

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Sixth International Conference on Fracture

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26 February 1985

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U.S. Office of Naval Research, London

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b RESTRICTIVE MARKINGS:

2a SECURITY CLASSIFICATION AUTHORITY:

2b DECLASSIFICATION / DOWNGRADING SCHEDULE:

3 DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited

4 PERFORMING ORGANIZATION REPORT NUMBER(S): C-2-85

5 MONITORING ORGANIZATION REPORT NUMBER(S):

6a NAME OF PERFORMING ORGANIZATION: US Office of Naval Research Branch Office, London

6b OFFICE SYMBOL (If applicable): ONRL

7a NAME OF MONITORING ORGANIZATION:

6c ADDRESS (City, State, and ZIP Code): Box 39, FPO, NY 09510

7b ADDRESS (City, State, and ZIP Code):

8a NAME OF FUNDING / SPONSORING ORGANIZATION:

8b OFFICE SYMBOL (If applicable):

9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

8c ADDRESS (City, State, and ZIP Code):

10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification): Sixth International Conference on Fracture--(UNCLASSIFIED)

12 PERSONAL AUTHOR(S): Kenneth D. Challenger

13a TYPE OF REPORT: Conference

13b TIME COVERED: FROM ______ TO ______

14 DATE OF REPORT (Year, Month, Day): 26 February

15 PAGE COUNT: 8

16 SUPPLEMENTARY NOTATION:

17 COSATI CODES

FIELD	GROUP	SUB-GROUP
11	04/06	
13	13	

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number): ~~Fracture~~ Fracture mechanisms, ~~Fatigue~~ Fracture mechanics, Composite Materials, Ceramics, Residual Stress, Nonmetallic materials, Fiber Reinforced Composites

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The Sixth International Conference on Fracture was held in New Delhi, India, in December 1984. This report discusses work on the mechanisms of fracture, mechanics, fracture of nonmetallic materials, composites, and dynamic fracture. US and UK scientists and engineers are setting the pace for development in the field of fracture; but there are major research programs in Japan, Australia, France, West Germany, India, and China. The use of fracture mechanics for safety analysis and residual life estimation is widespread, but its use in design is still quite limited.

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21 ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

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22c OFFICE SYMBOL: 11

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE: UNCLASSIFIED

SIXTH INTERNATIONAL CONFERENCE ON FRACTURE

Engineering materials can fracture by many different mechanisms. With the continuing increase in the understanding of these mechanisms and increasingly sophisticated design-analysis tools, engineering structures are being designed with much more confidence than ever before.

The science of fracture mechanisms has evolved over the past 20 years, but the many recent advances arising from mathematics, mechanics, and materials research have brought fracture mechanics to the level of maturity where it can be used in design and in the assessment of residual life after a period of operation or when a flaw has been detected. However, with very few exceptions, fracture mechanics is not applied in national and international design codes and standards. The only mandatory use is found in the standards for the nuclear energy industries in France, West Germany, the UK, and the US. In general the codes and standards seem to rely upon good materials to resist fracture and good workmanship to reduce the probability of defects.

The subject of fracture is multidisciplinary, requiring a background in metals science, mechanics, and mathematics. Without a coordinated effort by experts in these fields, the field of fracture mechanics could not have evolved to its present level. Professor T. Yokobori founded the International Congress on Fracture (ICF) in 1965 in order to provide a forum for the interaction of the experts in these fields. Since then there have been six international conferences all over the world. The Sixth International Conference on Fracture was held in New Delhi, India, from 4 through 10 December 1984. Over 500 papers were presented by participants from over 50 countries, making this the largest ICF ever.

The conference was especially well organized by Drs. S.R. Vallari (Director of the Aeronautical Development Agency, Bangalore, India) and P. Rama Rao (Director, Defence Metallurgical Research Laboratory, Hyderabad, India). The highlight of the meeting was a series of 32 plenary lectures by the leading authorities on fracture mechanisms and fracture mechanics. The ICF Honor Lecture was presented by Professor Roy Nichols, Head of the Risley Nuclear Power Development Laboratories, UK Atomic Energy Authority, Risley.

The ICF Honor Lecture

The theme of Nichols' paper was the use of fracture mechanics as an engineering tool. He emphasized a point that I mentioned earlier: presently fractural mechanics is used mainly after the fact to assess a design, but only rarely is it used in the design process. He stressed that the design codes and standards must be written in a way that fracture mechanics calculations performed by different people will give the same results. At present the design codes and standards are too vague and ambiguous for the engineer to follow their intent.

The main problems requiring research are: (1) the analysis of short (less than 1-mm-long) cracks, (2) weld improvement, (3) improvement in nondestructive testing methods, and (4) the development of a simple laboratory test for fracture toughness that can be used for quality control.

With today's structural materials it should be possible to allow for some crack extension because, in most of these materials, the stress intensity required to grow a crack once it has been initiated is higher than that required for initiation. However, this apparent increase in toughness once a crack has been initiated is not fully understood, and therefore the designer feels uncomfortable unless crack initiation is avoided. Thus, the full advantage of these high toughness materials is lost. Research must continue so that stable tearing in laboratory tests can be correlated with the fracture of large structures. Until this can be done satisfactorily, structures will continue to be repaired unnecessarily (often causing more problems than the defect), and they will be designed with unnecessarily conservative design rules. Pipelines and ships have long been designed for crack arrest rather than against crack initiation. However, there is still a very large uncertainty in defining the conditions which will lead to the arrest of a crack. Again, much more evidence from large-scale structural tests is required before this approach can be adopted for pressure vessel design.

Nichols pointed out several examples of the usefulness of fracture mechanics. Today many structures operate with known defects (that have been shown to be safe using fracture mechanics concepts), which only a few years ago would have been repaired or replaced. As our knowledge grows we are beginning to "learn to live with defects." Another important use of fracture mechanics is in the selection of materials; the fracture toughness is chosen to provide the specified maximum flaw size in the structure such that crack initiation will be avoided. Nichols has an excellent perspective of the field and the importance of research; he warns that the research must be carried to the point that it can be used by the design engineer otherwise its only use is for intellectual gratification.

Nichols' opening address set the theme for the conference, which I will highlight in the rest of this report.

Mechanisms of Fracture

Elevated Temperature. One of the largest problems facing both the materials and the design engineer is how to extrapolate the results of laboratory tests to actual operation. Professor M.F. Ashby (University of Cambridge, UK) has made a very valuable contribution toward the solution of this problem. He has developed techniques for mapping the various mechanisms which control deformation and fracture. The maps present these mechanisms as a function of the loading conditions (such as temperature, strain rate, and stress). These maps are based on mathematical models of the actual deformation and fracture mechanisms, and thus if the loading conditions in service are known, the laboratory conditions which will result in the same deformation or fracture mechanism can be selected. He presented his newest concept, developed with B.F. Dyson of the National Physical Laboratories, Teddington, UK. They have mapped tertiary creep, regarded as an instability by designers and thus to be avoided. All of the mechanisms that could be responsible for tertiary creep in several different alloy system have been modeled. Their approach is somewhat simplistic as each mechanism is treated separately, but they do recognize that the maps must be further developed to include possible interaction among the damage mechanisms. Even with this limitation, this work is a giant step forward as compared to the empirical methods for predicting the onset of tertiary creep.

D.M.R. Taplin, N.Y. Tang, and H.H.E. Leipholz (Trinity College, Dublin, Ireland) are developing similar maps for the damage caused by combined creep (static loads) and fatigue (cyclic loads) in aggressive environments. Their maps predict that the frequency effect (fatigue life decreases as the cyclic frequency decreases) is mainly due to environmental effects rather than due to creep damage accumulation. (Note: my paper in this conference on the mechanisms of fatigue damage in ferritic steels at elevated temperature reached this same conclusion.) Their model predicts a critical frequency at which creep damage will occur, but this frequency is below that used for almost all laboratory tests.

One thing that is clear from these papers and the others on mapping at this conference: much more thought of this type (what are the damaging mechanisms, when does each mechanism control the damage process, how do they interact with each other) must precede any laboratory testing program in which data are being generated in order to develop design correlations. Without this forethought, it is very likely that the mechanical property or fracture correlations developed will not extrapolate correctly from the laboratory test conditions to the actual operating conditions because the correlations will be based on the wrong damaging mechanism.

Fatigue. Fatigue failures continue to plague the designers of engineering structures--primarily because of a lack of understanding of the behavior of cracks in their working environment. The problem is that cracks have very complex geometrical shapes, are created in many different ways, are influenced by the nature of the environment to which they are exposed, and are affected by the cyclic-stress state to which they are subjected. This latter point was discussed in a paper by K.J. Miller and M.W. Brown (Sheffield University, UK). Their experiments have shown: (1) the threshold for crack initiation is very dependent on stress state, (2) the orientation of the crack in the stress field is very important, and (3) the tresca yield criterion is the best method to describe the cyclic stress-strain behavior, but one must use fracture mechanics to predict fracture.

R.O. Ritchie (University of California, Berkeley) presented a review of the factors which control fatigue crack growth at the very low crack-growth rates near the threshold for fatigue crack growth. This crack growth regime is important because many structures are designed to avoid any growth of preexisting flows. But since many factors influence the threshold cyclic-stress intensity for crack growth, the experimental measurement of the threshold is difficult, and the use of this threshold in design requires a very accurate estimate of the operating conditions of the component. He emphasized that crack growth in the near threshold regime is strongly influenced by crack deflection and crack closure. Load ratio, variable amplitude loading, grain size, slip mode, and environment all influence the threshold value. Both crack closure and crack deflection act to vary the local (crack tip) driving force. He further shows how this can affect the extrapolation of the laboratory data to predict component life.

Microstructural Effects on Fracture. The microstructure of a metal is known to control the fracture resistance of metals. J.F. Knott (University of Cambridge, UK), one of the leading authorities on this subject, discussed his recent work. *ESN* 38-9:491-492 (1984) discusses this work in detail; I only wish to reemphasize that his work on "short" cracks (less than 1-mm long) is leading to a solution of the problem associated with the analysis of the behavior of these cracks.

Fracture Mechanism Maps. Ashby has collaborated with D. Teirlinick and J.D. Embury (McMaster University, Canada) on the development of fracture maps for ductile fracture. The same basic approach is used in the development of these maps as I discussed earlier for tertiary creep. The various mechanisms controlling ductile fracture (particle-matrix interfacial strength, shape and distribution of particles, hydrostatic pressure effects on interfacial strength) have been incorporated into mathematical models that quantify the roles of these variables in competition among the various fracture mechanisms when variables such as microstructure, superimposed hydrostatic pressure, or temperature are changed.

Mechanics

Overload Effects. Ma Delin (Baotou Institute of Metallic Materials, Baotou, Nei Mongal, China) has developed a dislocation model that explains the growth behavior of a fatigue crack following single or multiple overloads. Once a fatigue crack is growing under the influence of a stable cyclic load and the cyclic load is subsequently increased for either a single or a few cycles, the crack growth rate, once the previous stable cyclic loads are imposed, is gradually retarded--reaching a minimum rate and then subsequently increasing back to the pre-overload rate.

Ma Delin's dislocation model defines the changes in the crack tip opening displacement (CTOD) in a clear and physically realistic manner. The model can also consider the combined effects of residual stresses and crack closure, both very difficult to explain. The approach is quite complex but seems to elegantly model the plastic deformation at a crack tip, and thus should accurately describe the CTOD, a result that has broader application than just for CTOD-controlled fatigue crack growth.

Residual Stresses. The effect of residual stresses on fracture resistance is a poorly understood but crucial topic. It is well known that welding induces residual stresses that are on the order of the yield stress of the material. In order to incorporate this fact into design analysis it is usually assumed that any defect present is subjected to a tensile stress of this magnitude before any external loads are applied; because very little is known about the distribution of the residual stresses, the worst possible situation is assumed. Often this approach leads to a highly conservative design (for example, when the defects lie in a region where the residual stresses are compressive).

R.H. Leggatt (The Welding Institute, Abington, UK) presented an analysis of the various methods used for the assessment of defects in the post-yield (elastic-plastic) regime and the variety of different methods for including residual stresses in these analyses. Leggatt compared linear elastic solutions (linearization, crack-face methods and initial strains) and post-yield fracture assessment criteria procedures (CEGB "R6" with and without strain hardening, see *ESN* 38-8:432-434 [1984]; a modified CTOD procedure; British standard BS PD6493; and an extended J-estimation procedure).

Figure 1 presents the results of Leggatt's comparisons. The insert shows an idealized distribution of residual stresses in the long center-cracked panel of A533B steel that was analyzed.

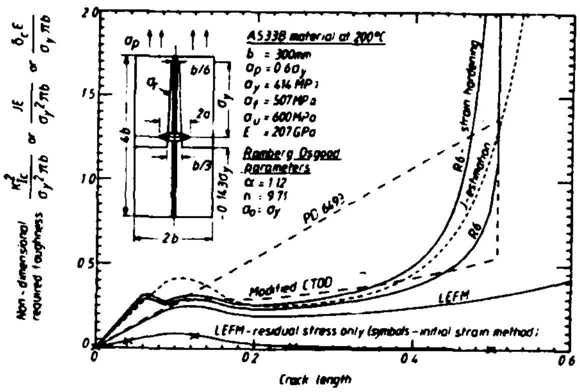

Figure 1. Nondimensional required toughness curves for welded center-cracked panel.

The required toughness (calculated by the various analytical methods) in order to avoid fracture under an applied tensile load, σ_p, of 60 percent of the yield stress is plotted as a function of a/b, the ratio of crack length to panel width. Crack growth should occur if the value of the required toughness is exceeded by the loading-residual stress conditions. The important result is that, with the exception of the linear elastic solutions and the BS PD6493 method, all of the methods closely agree in their predictions. They all illustrate a residual-stress dominated-region for small cracks and an applied-stress-dominated region for long cracks, with plastic collapse of the panel occurring around a/b=0.5--i.e., when 50 percent of the width of the panel is cracked. That all of these post-yield methods agree so well is important because it means that although different countries may use different methods, the end result (that is the integrity of the component) agrees.

Fracture of Nonmetallic Materials

Polymers. Several papers were presented, but the best of these was by A.S. Argon and his colleagues at the Massachusetts Institute of Technology. They have been studying the fracture mechanisms in polymeric materials for some time. Their paper clearly describes the current understanding on this subject for glassy polymers such as polystyrene. The researchers discussed the principles for toughening glassy polymers by controlled crazing and presented several examples of specially prepared heterogeneous polymers (glassy polymers with blends and emulsions of block polymers) which demonstrated these principles.

When glassy polymers are stressed they often exhibit crazing. This crazing plays a dual role. In homo-polymers the crazing usually grows from surface imperfections which can lead to fracture before much of the volume has undergone crazing; the overall behavior is brittle. However, if the polymer incorporates some compliant heterogeneities, the initiation of crazing can be spread more uniformly throughout the material. This results in plasticity and toughness. Although these tough glassy polymers have been produced commercially for decades (high-impact polystyrene), an understanding of the controlling mechanisms has only occurred recently. Argon has developed a model for craze initiation and growth as a function of the volume fraction and distribution of rubbery domains incorporated into the glassy polymer.

One very important aspect of the mechanism for crazing needs--and is receiving--further attention: the interface structure between the particles and the matrix and how this influences the initiation of crazing.

Ceramics. M.V. Swain and L.R.F. Rogi (Advanced Materials Laboratories, Melbourne, Australia) described the various methods used for toughening ceramics and the underlying mechanisms. They discussed the toughness of materials based on zirconia. Crack front bowing, microcracking, fiber reinforcement, transformation toughening, and crack plane deflection were all discussed with respect to their beneficial effect on toughness. The most recent advances have been with the last two mechanisms. MgO, CaO, Y_2O_3, or rare earth oxides partially stabilize the cubic phase such that precipitates of tetragonal ZrO_2 are present. These will undergo a stress-induced martensite transformation to monoclinic ZrO_2 which reduces the tensile stress at a crack tip as the transformation involves a dilitation.

In addition to relaxing the stresses at the crack tip, these transformed precipitates also cause crack-front bowing and crack deflection both of which increase the energy required to propagate a crack.

The researchers illustrated that ZrO_2 partially stabilized with MgO will exhibit R-curve behavior (stable crack growth) but that the transformation toughened material exhibited better toughness than material toughened by the generation of microcracks at the crack tip.

Although great advances have been made (both theoretically and experimentally) in understanding the toughening mechanisms in ceramics, this remains a topic on which much more research should be done; the payoffs are potentially great. With the recent advances in the production of high-quality ceramic fibers, the toughness of ceramics will occur by incorporating multiple toughening mechanisms in these materials. The subject of toughness testing and mechanisms of fracture in composite materials was another important topic discussed at this meeting.

Composite Materials

Concrete. Concrete, mortar, cement, and fiber reinforced concrete have all been studied using fracture mechanics concepts. However, no unique material parameter has been found that can quantify the fracture resistance of these materials. The plane strain fracture toughness, K_{IC}, which is a material property in the same sense that the yield strength is a material property for metals, has been measured for materials such as concrete cement, and mortar, but the reported results vary widely for similar materials. S.P. Shah (Northwestern University, Evanston, Illinois) explained why this is so and proposed a theoretical model which will reduce this problem. He feels that there is scatter in the results because a substantial amount of stable crack growth occurs before the peak load (when fracture of the specimen occurs). The fracture process involves the formation of a nonlinear fracture zone surrounding the crack tip (analogous to the zone of plastic deformation at the crack tip in metals). The fracture process zone includes a region in front of the crack tip, where microcracking occurs, and a region behind the crack tip where interlocking occurs. Shaw has developed a theoretical model to incorporate these effects into the evaluation of the toughness of these materials. The model divides the cracked region into three zones: traction free, fiber bridging (behind the crack front), and the matrix process zone (in front of the crack tip). The model accounts for changes in the matrix process zone which are specimen-geometry dependent, and in doing so provides a method to calculate the fracture resistance of a crack in a specimen of any geometry.

Fiber Reinforced Composites. The application of fracture mechanics and the understanding of the fracture mechanisms in these materials lags far behind the need for composite materials as viable structural materials. Progress in the development of these materials has been directed mainly at fabrication methods and simple laboratory testing. G.C. Sih (Lehigh University, Bethlehem, Pennsylvania) emphatically points out that the fiber/matrix interfacial properties are extremely important in understanding and modeling fracture. However, these properties are also extremely difficult to measure. He recommended that a structure should be designed such that the interface properties are not important and gave examples of how this could be done.

B.W. Anderson (British Aerospace PLC, Preston, UK) presented what turned out to be a rebuttal of Sih's ideas. He feels that Sih's ideas are too simplistic and that it is impossible to avoid the problems of interface breakdown by design, because of fabrication problems such as tapering and warping. For example, in order to prevent warping of a flat panel due to difference in orthogonal expansion coefficients, the optimum laminate stacking sequence is +45 degrees, -45 degrees, -45 degrees, +45 degrees, etc. However, this is not the optimal stacking sequence in order to avoid fiber/matrix interface loading, which is +45 degrees, -45 degrees, +45 degrees, -45 degrees, etc.

Anderson also believes that much more research into the methods for buckeling analysis of composites is required. At present they design with the objective of avoiding buckeling conditions as much as possible because they do not trust the present analysis method.

H.W. Bergmann (German Aerospace Research Establishment [DFVLR], Braunschweig, West Germany) gave an excellent review of damage mechanisms in fiber reinforced composites. As previously mentioned, the fracture process in composites involves many different failure modes simultaneously: matrix cracks, interfacial debonding, fiber breaks, and delamination between adjacent plies are all possible. The free edges of multidirectional laminates are particularly susceptible to cracking and delamination. The enforced compatibility between adjacent plies causes interlaminar shear stresses when these composites are subjected to axial loading. The magnitude of the stress is a function of the orientation of the plies. The work at DFVLR has shown that (90 degrees, ±45 degrees, 0 degrees) laminates have lower interlaminar shear stresses that other stacking sequences. Fatigue tests on two different composites (90 degrees, ±45 degrees, 0 degrees) and (0 degrees, ±45 degrees, 90 degrees) clearly revealed the superiority of the (90 degrees, ±45 degrees, 0 degrees) composite. DFVLR has many more tests in progress to study the damage mechanisms and the tolerance of fiber reinforced composites to flaws.

Dynamic Fracture

The concern with the possibility of incipient flaw propagation during a rapid cool-down of a thick-walled nuclear-reactor pressure vessel has motivated many research programs to study a metal's response to dynamic fracture. Although the research has been motivated by this situation, there is also the need to design against dynamic fracture in pressurized pipelines, ships, and other structures. Most of the experimentation in the past decade attempted to adapt the methods used for quasi-static fracture testing. However, these studies essentially ignore the fact that the driving force for crack propagation is a wave function at the crack tip.

The high-speed recording devices necessary to record the fracture process at high speeds has been developed at the Institut für Festkörpermechanik, Freiburg, West Germany, under the direction of Professor H. Schardin. The initial analytical work resulted in the development of closed form solutions for the dynamic stress fields at both stationary and running cracks. A major drawback of these solutions is that they can only deal with crack growth in a straight line, and, of course, the solutions do not apply to finite bodies except for the brief initial transient behavior. In order to overcome these difficulties, today's methods use finite difference and finite element analyses. Even with these methods, analyzing the case of crack branching is still a major problem.

Experimentally the resolution of the details of the stress fields near the crack tip under transient conditions is limited to within about 0.1 mm of the crack tip. However, the region at the crack tip is exactly where the events controlling the fracture process are taking place. Thus, until some new experimental method is developed the analyst must continue to infer the stress field in this region. Small test specimens experience multiple stress-wave reflections which can tend to mask and smear out wave effects such that the extrapolation of the laboratory results to large structures is very tenuous. Therefore, in the future it would seem that researchers should concentrate on high temporal and spatial resolution in their experiments and much more careful analytical examinations of the laboratory experiments.

Much of the above discussion of dynamic fracture is abstracted from a plenary paper given by W.G. Knauss (California Institute of Technology, Pasadena, California). A number of papers were presented on the mechanisms of dynamic fracture, stress field analysis methods, and experimental methods, but none of these presented any results that would help to solve the problems mentioned previously.

Conclusions

If it is possible to draw conclusions regarding the relative research efforts of various countries in the field of fracture from this conference, then one must conclude that the US and UK scientists and engineers are setting the pace in the development in this field; but there are major research programs in Japan, Australia, France, West Germany, India, and China. The use of fracture mechanics for safety analysis and residual life estimation is widespread, but its use in design is still quite limited. Engineering schools around the world are just beginning to teach the subject at the undergraduate level.

Perhaps the main reason fracture mechanics is not more widely used in design is that the correlation between laboratory test results and the behavior of engineering structures is still questioned. Thus, more large-scale component testing must be carried out in order to improve confidence in this correlation.

Materials with improved fracture resistance continue to be developed as the level of understanding of the controlling fracture mechanisms increases. In particular, recent advances in steel making, which have resulted in improved cleanliness and chemical homogenity, have produced steels with improved and consistent fracture toughness. To take advantage of these improved materials, we must learn more about the mechanisms of stable tearing and about how to allow for this in design. By limiting loads to those which prevent crack initiation, many designs are unnecessarily conservative. For the same reasons, we must learn more about the mechanics and mechanisms of crack arrest and dynamic fracture.

Welds still represent regions of potential problems because defects will exist in regions where the microstructures have less fracture resistance than the bulk material, and these regions also experience high residual stresses. There is evidence of an increase in the research dealing with these problems. This must continue before the designers will know how to analyze a welded structure as well as they can a non-welded structure. The improvement in nondestructive examination (NDE) techniques will help in this area because the expected defect size in welds will decrease in proportion to the ability of NDE to detect smaller defects.

The conference proceedings are available (all six volumes) from Pergamon Press Inc., Maxwell House, Fairview Park, Elmsford, New York, 10523. The next ICF Conference will be held in Houston, Texas, in 1989.